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Two-Dimensional Interdigitated Pixel Detector for Energetic Particle Spectrometers

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ABSTRACT

This paper describes a type of cosmic ray detector suitable for the construction of a small, low power space-based instrument to detect the energy and isotope of energetic nuclei, such as those produced by solar flares. The detector is similar to previous types of silicon PIN detectors where the fully depleted body of the wafer comprises intrinsic region of the PIN structure. The novel aspect of this detector is that the one surface is divided into a two-dimensional array of pixels, and that the collected holes are divided between a row and a column collector in each pixel, yielding both dimensions of position information from this side of the detector. in a conventional PIN detector, both sides are divided into stripes, and each side provides one dimensional information. A single large area collector on the opposite side of this new detector is used to determine the energy of the incident nucleus. This scheme requires only a single precision pulse-height amplifier connected to the broad area contact, rather than one for each strip, as in the conventional scheme, resulting in a significant reduction in the mass, power and complexity of the readout electronics. The design, fabrication, and operation of such a detector is discussed, Initial particle tests show a prototype to be functional. The projected power saving "of using such a detector is presented.

1. INTRODUCTION

Measurements of the elemental and isotopic composition of energetic heavy nuclei in space provide crucial information for understanding the origin and evolution of several samples of matter that can not be easily investigated by other means, including the solar corona, the nearby interstellar medium, and galactic cosmic rays sources (see, for example, Waddington[1]; and Jones[2]). in addition such measurements are critical to studies of energetic particle acceleration and transport. For example, intense fluxes of energetic nuclei are frequently injected into interplanetary space in association with impulsive solar flares, coronal mass injections (CMEs), and interplanetary shocks. In addition, it is now generally believed that solar wind "pickup" and other ions are accelerated to energies greater than 1 GeV at the solar wind termination shock. Planetary magnetospheres, including the Earth, Jupiter, and Saturn, also accelerate particles 10 high energies and then store them for periods ranging up to years.

Typically, the composition of these energetic particle populations are dominated by H, He, and perhaps electrons, with heavier nuclei making up only a small fraction of the ions at a given energy/nucleem, For example, in large solar energetic particle (SEP) events the sum of all nuclei from C to Ni (Z=6 to Z=28) typically constitute approximay 1 10^{-3} of the ion population with energies greater than 10 MeV/nut, with individual isotopes accounting for anywhere from 10 to several times 10^{-4} of the total, Similarly, in the Earth's magnetosphere 7>2 nuclei appear to account for only about 10^{-5} of ions with >10 MeV/nuc. As a result, measurements of these rare heavy nuclei in space typically require instrumentation capable of operation in a hostile radiation environment where the flux of H, He, and electrons exceeds that of the particles of interest by many orders of magnitude.

One proven technique for energetic particle spectroscopy in space employs a "telescope" comprised of a stack of silicon solid state detectors (wafers of silicon typically -10 cm^2 in area and 0.1 to 1 mm in thickness). Fig. 1 shows an example of such a telescope that is planned for flight on the Advanced Composition Explorer in 1997.3 Energetic nuclei that enter the aperture of this telescope within an appropriate energy range will slow down and stop, depositing energy in two or more of the detectors. By combining the energy loss measurements from these detectors it is possible to determine nuclear charge, mass, and kinetic energy of incident nuclei over the element range from He to Ni (Z=2 to Z=28). Fig, 2, which includes data obtained at an accelerator with an earlier instrument of similar design, shows an example of how this technique can be used to measure both elemental and

Solar Isotope Spectrometer (SIS)

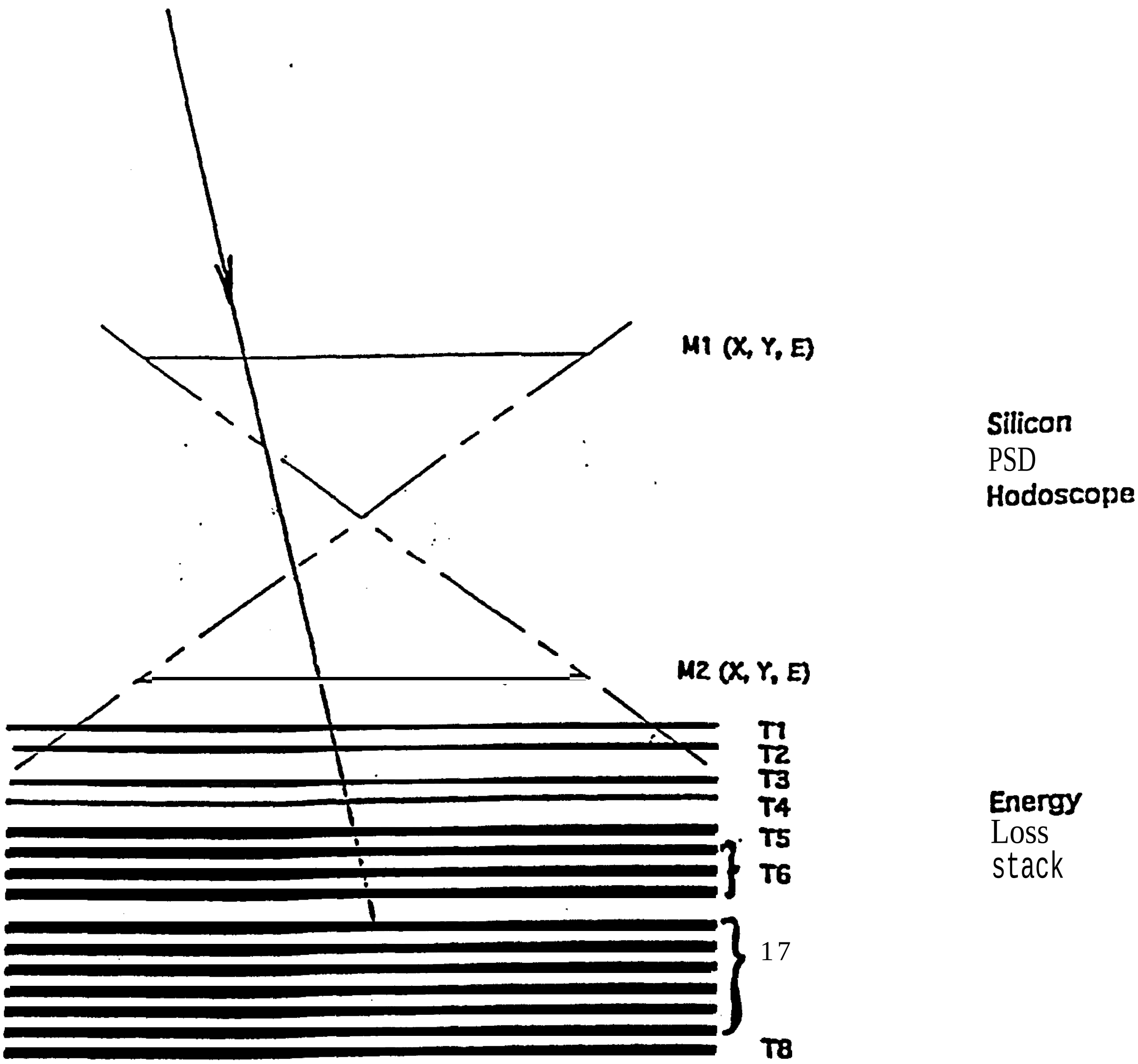


Fig. 1: Schematic illustration of one of two telescopes that comprise the Solar Isotope Spectrometer (SIS) that will be launched on ACE in 1997. All detectors are silicon solid state devices; the individual wafers range in thickness from 60 microns to 1 mm. Ml and M2 are two dimensional silicon strip detectors that measure both position and energy loss. T1 to T8 are all 10 cm in diameter.

isotopic composition. Note that it requires about an order of magnitude better resolution to resolve isotopes as it does to resolve elements.

In space, where particle populations are typically isotropic, it is also necessary to measure the trajectory of incident particles to obtain resolution sufficient to resolve heavy isotopes incident over a range of angles. To provide this trajectory information, silicon strip detectors are typically used as the first elements of the telescope (e.g., Fig. 1). In optimizing the design of an energetic particle spectrometer of this type there are typically several (often conflicting) requirements on the design of these Position-sensitive-detectors (PSDs):

1) Because the observed energy spectra of particles in SEPs, interplanetary shocks, and planetary magnetospheres typically decrease rapidly with increasing energy, there is an advantage to PSDs that can serve as both trajectory and energy measuring devices, in order to minimize the "threshold" energy of the instrument and thereby maximize the yield. Two-dimensional devices (that measure both x and y coordinates) also have an advantage.

2) As discussed above, studies of rare species typically require operation in a hostile radiation environment where as many as 10^5 to 10^6 low energy (>1 MeV) protons may hit the front detector per second. In such cases, accidental coincidences between low energy protons and the heavy elements of interest may lead to both incorrect trajectories and/or incorrect energy measurements. It is therefore necessary to track multiple particles in the PSDs to preserve isotope resolution.

3) To maximize the yield of rare species the area-solid angle product of the telescope should be as large as possible.

4) Finally, because space missions almost always place a premium on resources, the weight and power requirements of the electronics that instrument the PSDs should be minimized.

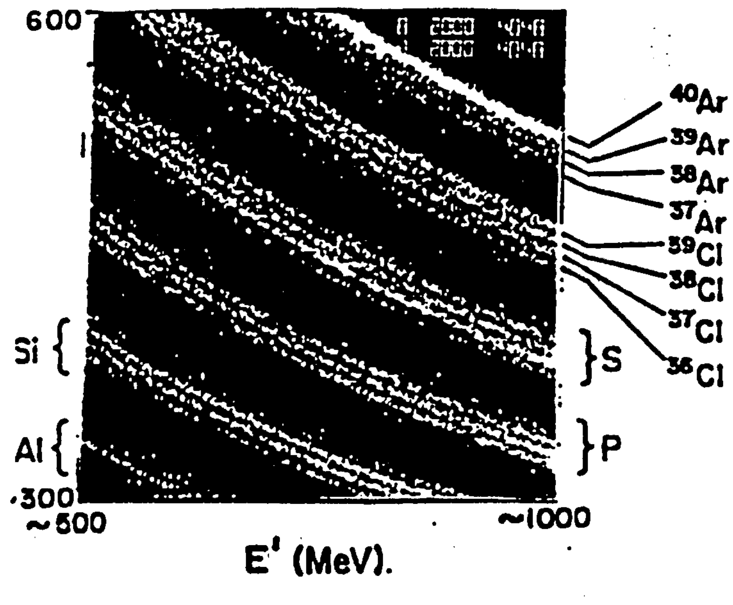


Fig. 2: On-line display of data obtained at the LBL Bevalac showing delta-E (measured in a 500 micron thick detector) vs. the residual energy (E') measured in a following detector. A beam of -300 MeV/nuc ^{40}Ar was incident on a target that fragmented many of the beam particles into lighter nuclei. Both elemental and isotopic resolution are evident in this display, in which each dot represents an individual stopping particle.

Past instruments of this type have typically employed one of two approaches to instrument the PSDs. If each strip is individually instrumented to provide both position and energy loss information (e.g., Althouse[4]), there are significant penalties in weight, power, and electronic complexity if the size of the detectors is increased to the point where many hundreds of strips are required. In a second approach that minimizes electronic complexity, the strips are attached to a resistive divider (e.g., Lamport[5]). However, this approach dots not resolve multiple particle trajectories and is therefore subject to chance coincidence effects.

In a collaborative effort involving Caltech and JPL, we have been developing a new Interdigitated Pixel PIN Detector (IPPD) in which two-dimensional position information is derived from a single side of the detector, while precise measurement of the energy deposition is derived from the opposite side (for a more detailed description, scc Cook c1 al.[6]). Thus, only a single high precision pulse height analysis (PHA) chain is required to read out the energy signal, while the individual rows and columns on the pixelated side can be read out with amplifier-discriminators implemented in low-power, high-density, custom VLSI. This approach can provide significant savings in mass, power, and overall system complexity.

2. TECHNICAL APPROACH

Fig. 3 illustrates the approach by which position information is derived from the IPPD. Each pixel is divided into two subpixels, onc associated with the "row" coordinate, and the other with the "column" coordinate. The subpixels form a pair of interdigitated contacts which should have a spacing smaller than the lateral spread of the electron-hole plasma generated by a typical particle of interest to ensure adequate charge sharing between the row and column subpixel.

The operation of each subpixel in this array is identical to that of conventional fully depleted PIN detectors, as illustrated in Fig 4. In a given row all row subpixels arc attached to a row wire that is brought out to the edge of the array. The column subpixels arc connected in a similar manner, A particle impact within any given pixel will deposit charge on both subpixels, which can be detected on the appropriate row and column wires, Equal sharing of the charge between the subpixels is not required. The detector readout electronics must discriminate which row and column have "fired", yielding the impact coordinates. The electronics can be designed to record multiple positions if two or more particles strike the detector in coincidence.

The opposite side of the detector collects all of the deposited charge independent of the position of the particle impact. Precision pulse-height analysis of this electrode will accurately determine the total energy loss of the particle. To recover accurate individual pulse heights of multiple particle events, an eventual detector might have several segments on this back electrode.

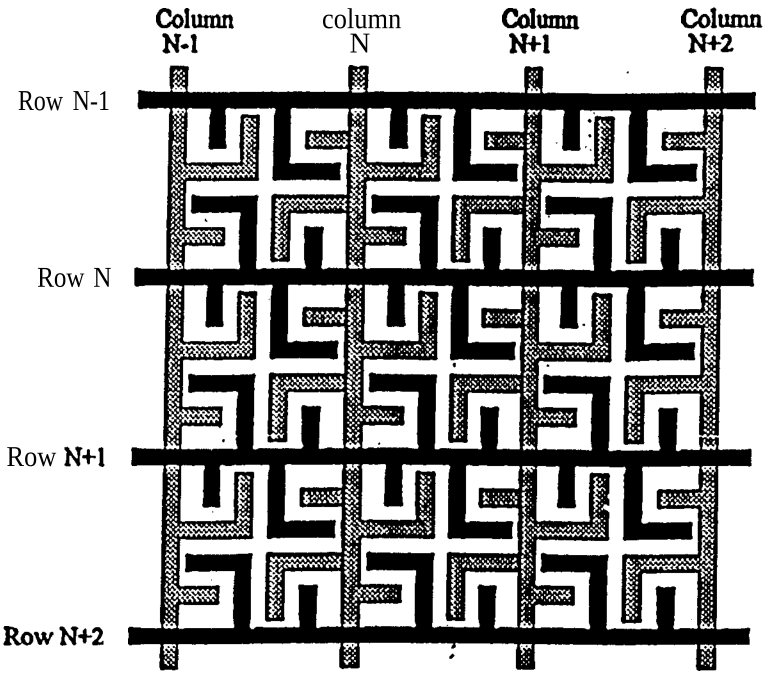


Fig. 3: Top view of a conceptual 3 x 3 IPPD array illustrating how two dimensional information is derived.

3. DESIGN CONSIDERATIONS

The prototype devices now under development have a size of -1 cm^2, including a 10 x *10* array of square pixels, sufficient to test the IPPD concept. Eventually detector diameters of 5 to 10 cm arc desirable. Pixel sizes of 0.5 to 1 mm arc adequate for many applications, although smaller pixel sizes arc possible. The prototype device.s arc 250 microns thick; potential applications might involve thicknesses ranging from -50 microns to -1 mm,

The width of the interdigitated fingers of the pixel must be small enough to ensure that the charge signal from a vertically incident nucleus is adequately shared between rows and columns. A simple analysis that takes into account carrier diffusion suggests that a spacing of-50 microns should be adequate for a 250 micron thick detector.[6] Prototypes arc being fabricated with finger pitches of 20, 40, and 80 microns in order to assess the charge sharing efficiency. Fig. 5 shows an example of the interdigitated finger pattern for a single unit cell of the array. Such a cell contains the quarters of four pixels. The full prototype array is shown in Fig. 6. Additional design considerations arc discussed in Cook. [1]

4. DETECTOR FABRICATION AND TESTING

The prototype detectors have been fabricated using a custom process at the MicroDevices laboratory at JPL. The starling material is a 2-inch wafer 250-microns thick made of 8-10 kΩ-cm resistivity silicon. A 1-micron thick polysilicon layer that is heavily doped with phosphorous is deposited on the unpolished side of the wafer, and this is capped with a 1-micron thick vapor deposited low temperature oxide (LTO). The doped polysilicon serves two purposes. First, it serves to dope the monocrystalline silicon beneath it to form the n-layer of the PIN structure, and to allow contact to this layer. Second, the combination of grain boundaries, defects, and phosphorous complexes serve as getters to trap impurities that might otherwise be introduced into the bulk of the wafer during high temperature processing. This gettering action preserves the high resistivity of the intrinsic part of the detector. The polysilicon layer and cap were deposited by ERL Microlabs of the University of California at Berkeley, using a process developed by Steve Holland of the Lawrence-Berkeley Laboratory.[7]

A 0.5-micron thick steam oxide is grown on the polished side at 1000 ‘C, and is patterned by photolithography using buffered oxide etchant (BOE) into the interdigitated finger pattern. After the photoresist is removed, the sample is implanted with boron at a dose of 3×10^{14} cm^{-2} and an energy of 35 keV, using the steam oxide as a mask. After implant the steam oxide is removed in BOE. A photoresist layer is used on the back to preserve the LTO capping the polysil icon for both BOE etches. The implant is activated al 900 ‘C for 1 hour. An oxygen ambient is used for 20 minutes of this anneal in order to form a 400 Å oxide. Openi ngs arc made in the oxide using photolithography with BOE. First metal (aluminum) is deposited and pat terned, then a 0.5-micron silicon dioxide dielectric is deposited by electron cyclotron resonance chemical vapor deposition, Openings in the dielectric arc made, and the second recta] (also aluminum) is deposited and patterned. The LTO is removed from the backside using buffered HF, and alumi num backmetal is deposited to contact the n-type polysilicon. Lastly the wafer is sawed into individual die, which arc then packaged and wire bonded.

All of the arrays presently have been of 1 mm square pixels arranged in a 10x10 array, with the first and tenth pixels being ha]f-pixels, making the total prototype array area approximately 1 square centimeter. A guard-ring surrounds the array. A total of 9 arrays can be made out of a 2-inch wafer. Presently, the mask layout includes two copies of the arrays for each of the pixel with the 20 and 80-micron finger pitch, three copies of the army with the 40-micron finger pitch, and two copies of a test array that contains various test structures, including broad area detectors and capacitors.

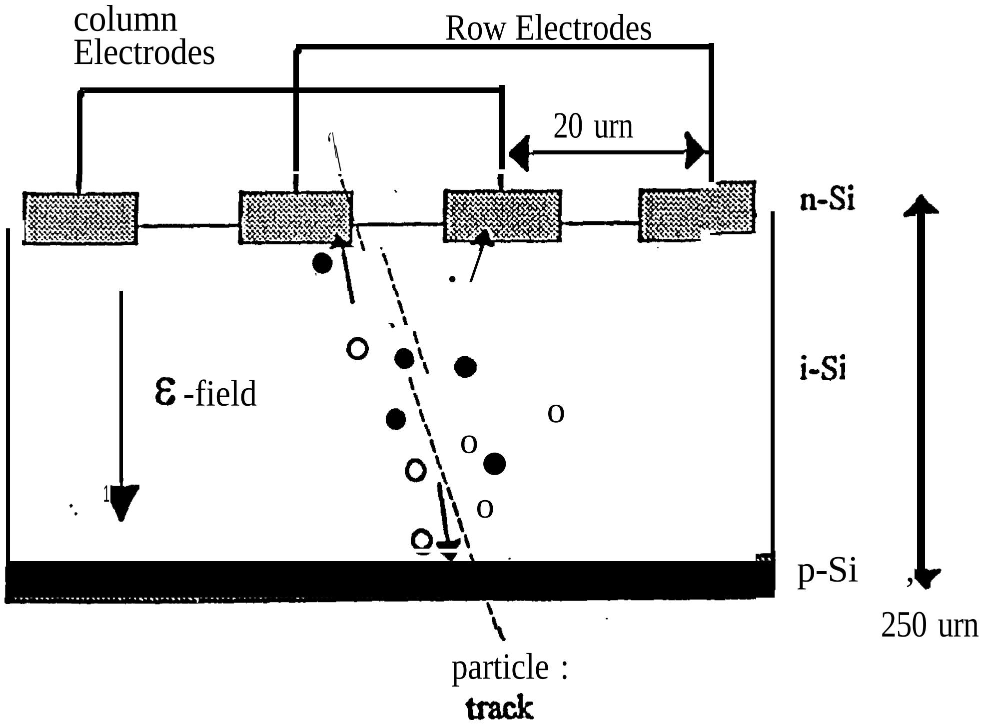


Fig. 4: Schematic cross section of an IPPD pixel. The passage of a charged particle leads to hole collection at the interdigitated row and column electrodes (p-doped) and electron collection at the n-doped contact at the opposite side of the device.

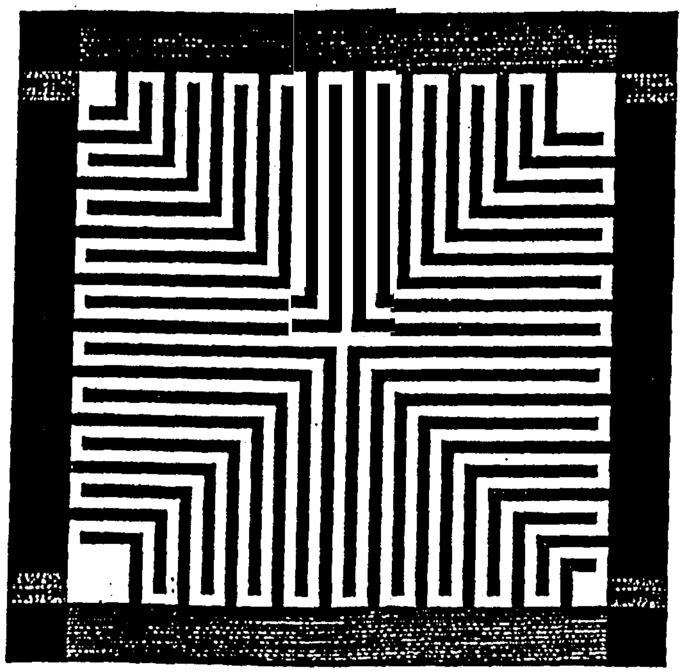


Fig. 5: Interdigitated row and column pattern within a single 1 mm x 1 mm unit cell in which the electrode pitch is 40 microns, A unit cell contains the quarters of four pixels.

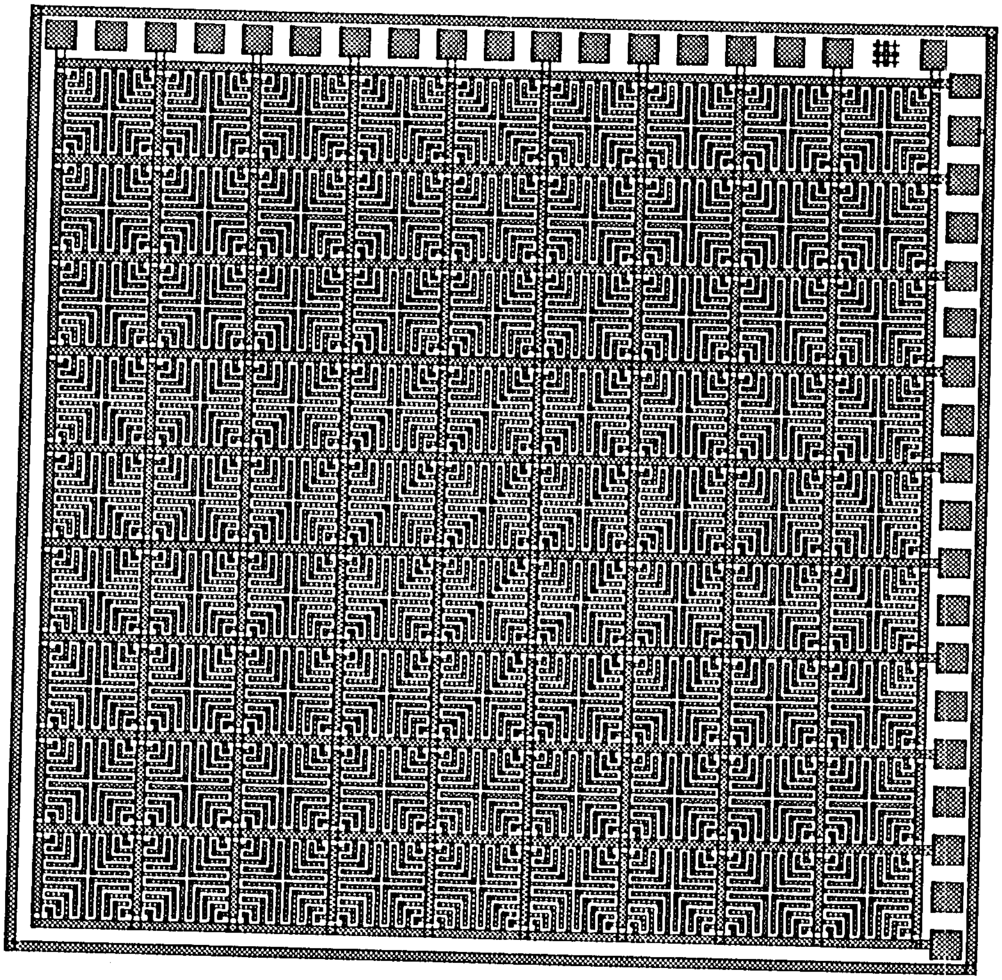
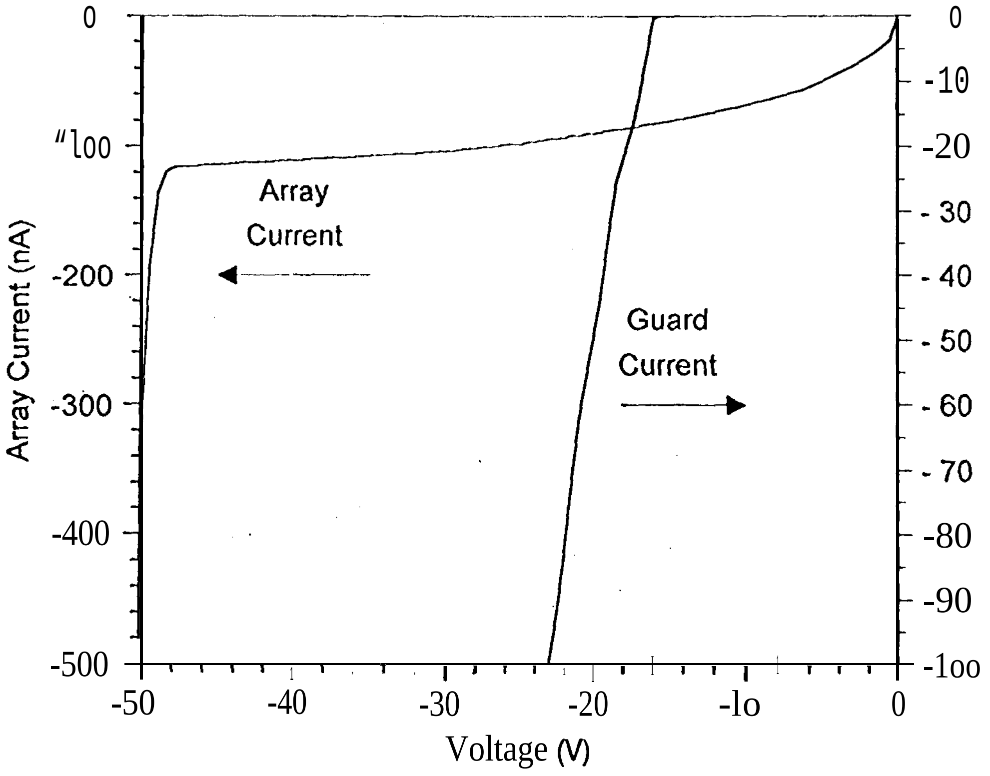


Fig. 6: A 10X1O IPPD array including a guard ring.

The detectors have been tested electrically, including functionality tests and a characterization of the dark current, Typically all of the row and column 1 i ncs show the expected diode behavior, with respect to the back contact. Occasionally, some column and row contacts arc shorted through metal bridges between fingers, but more than 70% of the arrays arc fully functional. The dark current of the entire array (with all rows and columns connected together), and the dark current collected by the guard ring as a function of applied bias is shown for an array with the 40-micron finger pitch in Fig. 7. The guard current exhibits a soft breakdown at about -20 V, and increases to -100 μA by -23 V. The compliance on the test set up was limited to 100 μA to prevent damage to the array. The total array current is less than 120 nA out to beyond -45 V, with a breakdown at around -48 V. It requires approximately -100 V to completely deplete the wafer. The current on the guard appears to be coming from the periphery of the die, possibly from the sawed edges. The breakdown for the array may bc related to a punch through from the array to the guard, since the guard voltage is limited by the compliance limit. The source of the peripheral current is under investigation, and ncw arrays arc being fabricated that include changes in order to eliminate it.

Energetic particle testing of the prototype IPPD detectors is only in its initial stages. However, tests with 5.5 McVAn~-241 alpha particles have demonstrated that the devices can successfully measure both particle energy and 2-dimensional position. With the alpha-source positioned -1 cm above the device a residual energy of -S McV is deposited in the detector, With 40 micron finger pitch it was found that reliable coincidences between individual row and column wires were obtained with the row and column discriminators set at -1/8 of the total deposited energy. As expected, the coincidence rate decreased when the discriminator levels were raised; with both row and column discriminators set above 50% of the alpha particle energy coi ncidences were no longer observed. A wide range of further tests arc planned to determine the efficiency and resolution of the devices, and to optimize their design.



Fig, 7: The dark current of the entire array (with all rows and columns connected together) and of the guard ring surrounding the array, as a function of applied bias, for an array with a 40-micron finger pitch. It requires approximately -100 V to fully deplete the detector. The soft breakdown of the guard and the subsequent punch through from the array 10 the guard prevents this array from being taken beyond an applied bias of -SO V.

5. DETECTOR READOUT ELECTRONICS

Readout of the detector array will be performed using custom VLSI circuits now under development for use in the S1S instrument to be flown on ACE, Each row and column will be pl]lsc-height analyzed with an independent linear chain consisting of a low-noise charge sensitive preamp, gated integrator, sample and hold, and a 12-bit Wilkinson-type ADC.[8] A single integrated circuit will contain 16 pulse-height analysis chains, each with an externally adjustable discriminator, with each chain consuming only -S mW. The energy signal from the other side of the detector will be pulse height analyzed with a standard circuit consuming ~40 mW. Thus, a typical detector for space flight applications, having SO rows and 50 columns, could be instrumented with a small number of integrated circuits consuming only --0.5 watt.

These chips arc being fabricated in the rad-hard 1.2 micron CMOS process of the United Technologies Microelectronics Center (UTMC), following extensive prototyping through MOSIS.

As an example of a practical application of the IPPD, we consider the S1S instrument under development for ACE (see Fig. 1). S1S has two telescopes, with a trajectory system that contains a total of four PSDs, each having 64 strips on both sides of the devices, for a total of S 12 individually analyzed strips. If these 512 strips were pulse-height analyzed using custom hybridized circuits such as those in the MAST instrument launched on SAMPEX in 1992,[9] the total power associated with the readout of these devices would be 512 strips x 110 mW/ADC chain = 56 W, a prohibitive amount. If instrumented using the custom VLSI circuits under development for ACE,[8] the required power would be 5 12 strips x 20 mW = 10 W. If the multi-strip devices in S1S were to be replaced by pixelated devices of the design described here, we estimate that the required power for the trajectory system could be reduced to S 12 strips x 5 mW + 4 x 40 mW = 2.7 W.

6. SUMMARY

in summary, the interdigitated pixel detector described here promises to provide both two dimensional position resolution and excellent energy resolution with significantly reduced electronic complexity, with potential applications in future space instruments that study energetic nuclei in a variety of environments. This device may also have applications in other areas of astrophysics, and in nuclear and high energy physics.

7. ACKNOWLEDGMENTS

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